Chandra Galaxy Atlas

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Abstract

The hot ISM in early type galaxies (ETGs) plays a crucial role in understanding their formation and evolution. Structural features of the hot ISM identified by Chandra (including jets, cavities, cold fronts, filaments and tails) point to key evolutionary mechanisms, e.g., AGN feedback, merging history, accretion/stripping and star formation and its quenching. In the Chandra Galaxy Atlas program, we have systematically analyzed the archival Chandra data of 80 ETGs to study the hot ISM. Taking full advantage of the Chandra capabilities, we have derived uniform data products of spatially resolved datasets with additional spectral information. We will make these products publicly available and use them for our focused science goals.

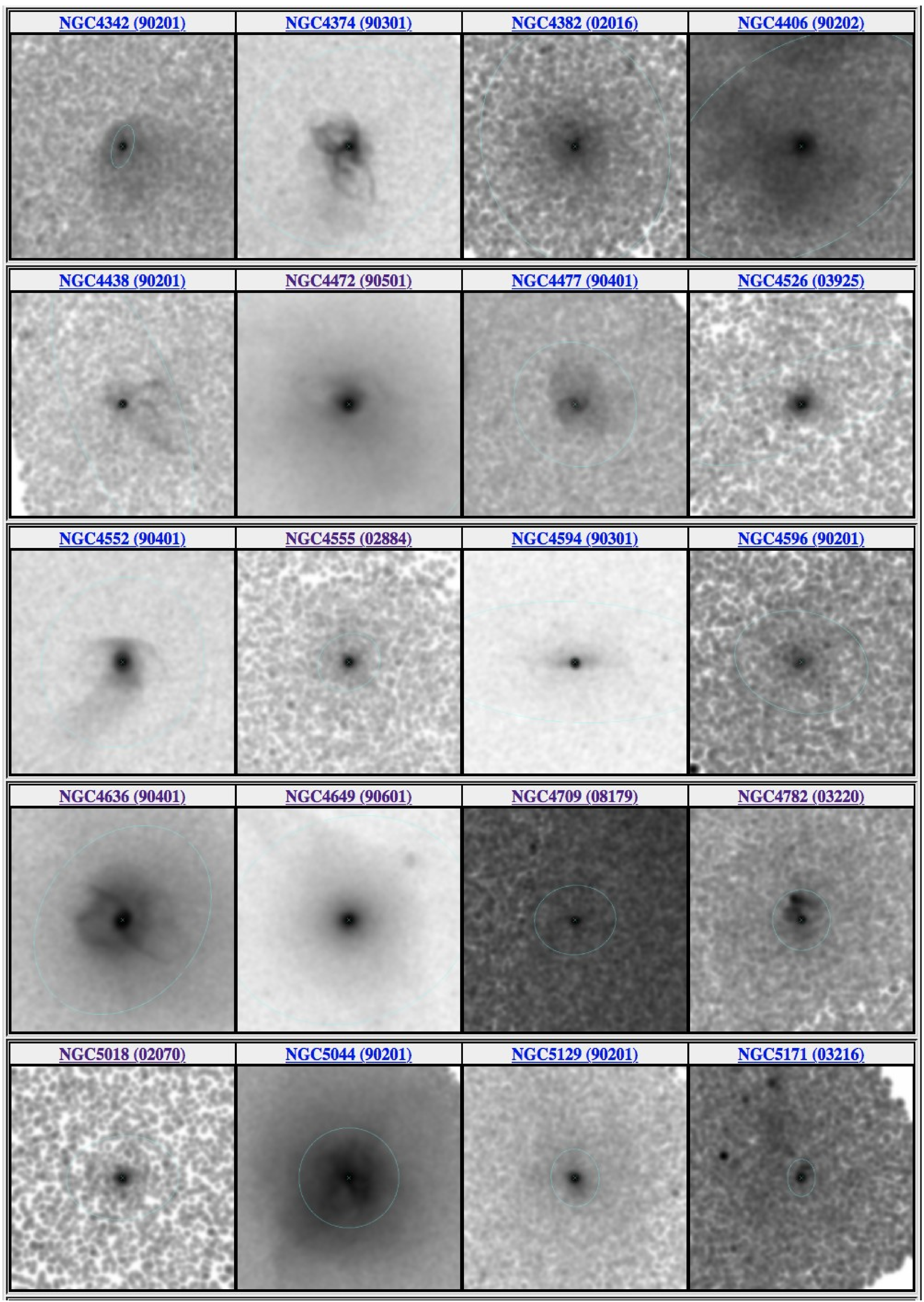


Figure 1. Image Gallery – a snapshot of our sample.
The images show the diffuse hot gas emission in each galaxy, after excluding point Sources and correcting exposure variations over the field of view. This illustrates how varied the hot gas distribution could be in different galaxies and how these various hot gas features are related to other fundamental properties of these galaxies, such as the activity of a central nucleus (AGN feedback), the environment and the interaction with it (sloshing, ram pressure stripping, etc.).

Data Processing Pipeline

Merge Datasets

45% of galaxy sample were observed multiple times over 15 years and can be merged.
For ACIS-I, we use data from I0-I3 (CCDID=0-3).
For ACIS-S, we use data from S2-3 (CCDID=6-7).

chandra_repro	reprocess the data to bring it to the same CALDB version
fluximage	create exposure-corrected images and exposure maps.
mkpsfmap	make psfmaps for the individual images for the requested CCDs
wavdetect	find sources for the individual images, used for reproject_aspect
reproject_aspect	correct aspect solutions with detected bright sources near on-axis
chandra_repro	reprocess each obsid using the new asol1.fits files
rm_bkg_flare	remove the background flare using deflare (sigma clipping)
acisreadcorr	correct for acis readout streak of very bright sources
reproject_obs	reproject each obsid onto the common tangent to merge evt files
flux_obs	make the exposure-corrected image for the merged evt file
get_sky_limits	get the merged file size to make the psf files the same size
fluximage	recreate the corrected images and exposure maps for each obsid
mkpsfmap	remake the psf files with the new images with the corrected sizes
dmimgcalc	make a weighted-mean merged psf files
wvdetect	find sources for the merged image with the merged psf file

See Figure 2 for an example of a diffuse gas image

2D Adaptive Binning

The most innovative step in this program is the use of four adaptive binning methods to most effectively characterize the 2D information:

1. Circular annuli with adaptively determined inner and outer radii, spanning a entire 360 deg or specific pie sectors **(AB)**
2. Weighted Voronoi tessellation (**WVT**) adaptive binning (Diehl & Statler 2006)
3. Contour binning (**CB**) which further takes into account the fact that similar surface brightness regions likely have similar spectral properties (Sanders 2006)
4. **Hybrid** binning which maintains a high s/n by extracting spectra from larger circular regions while keeping the spatial resolution in finer spatial grids (O'Sullivan 2014)

Spectral Fitting

*Spectral extraction (generating arf and rmf) for each spatial bin per OBSid and CCDid
*Fitting: Either simultaneously or after applying combine_spectra to spectrum, arf, rmf
*Model: primarily a 2-component model (VAPEC for hot gas and BREM for undetected LMXBs).
- When AGN or hotter ICM emission is present, extra components are added.
- For gas-poor ETGs, add active binaries and cataclysmic variables (Boroson et al. 2011)

*Background: sky bkg after re-scaling the bkg level at 9-12 keV (Markevitch 2003) Use the off-axis chip data from the same observation to correct for temporal and spatial variations of the soft X-ray background, whenever possible.

Science Goals

While the entire dataset will be available to the astronomical community, we plan to address several important science subjects:

Gas morphology

We will explore the 2D distribution of gas temperature and metal abundance. These 2D spectral maps can reveal special features, which are not visible in 1D radial profiles, e.g., an asymmetric temperature distribution (Figure 2) and an asymmetric Fe distribution (O'Sullivan et al. 2014).

Scaling relations

We will use the global quantities measured in our program (e.g., gas luminosity, mass, temperature, metal abundance) and compare them with other wavelength data to study correlations that may give us additional insight on the physical properties of the hot ISM and the evolution of the ETGs.

X-ray based mass profile

X-ray observations of the hot ISM can be used to measure the total mass (assuming hydrostatic equilibrium). We will first measure the non-thermal pressure by directly comparing X-ray and optical measurements of mass distributions for a dozen ETGs for which deep X-ray observational data, optical kinematics data of globular clusters (e.g., SLUGGS survey) and planetary nebulae (e.g., PNS survey) are available. Then we will derive the mass profiles to the extent that the X-ray measurement is valid.

Circum-nuclear gas

The properties of the circum-nuclear gas give important constraints to the AGN feedback, a key mechanism in the formation and evolution of ETGs (e.g., Paggi et al. 2014). Our program will yield a large sample of hot gas data near the center, allowing a statistical investigation of these properties, related to gravitational heating from the central SMBH, a recent AGN outburst, or interaction with confined nuclear jets.

LMXBs

Chandra-detected LMXBs in ETGs have been extensively studied to understand the stellar populations of ETGs via XLFs (e.g., Fig 4 in Kim & Fabbiano 2010) and their connections to GCs, merger histories, and the young stellar population. Our program will provide the most extensive homogeneous data set of LMXBs in ETGs currently available.

Data Products

Primary goal is to extract 2D spatial and spectral information on the hot ISM of ETGs.

- **X-ray images of diffuse emission**
  Raw and smoothed images will be generated in multiple energy bands after detected point sources are removed and filled by surrounding photons. Spatial exposure variation will be corrected and background emission subtracted.
- **Three color images** to visualize the 2D spectral variation.
- **High resolution images** in special regions of interest (e.g., circum-nuclear gas, cavities, filaments) obtained by applying the sub-pixel resolution algorithm.
- **Adaptively binned spatial regions and flux images**
- **1D radial profiles** of surface brightness (in multiple energy bands), gas temperature and element abundances (e.g., Fe and Si/Fe).
- **2D maps** for gas temperature, elemental abundances, pseudo-density, pressure and entropy
- **3D (de-projected) spectral parameters** including temperature, density, entropy, pressure
- **Global quantities** including total gas mass Mgas(r), and total gas luminosity Lx,gas(r), Lx-weighted (and M-weighted) mean temperature <Tx>, total virial mass Mtotal(r)

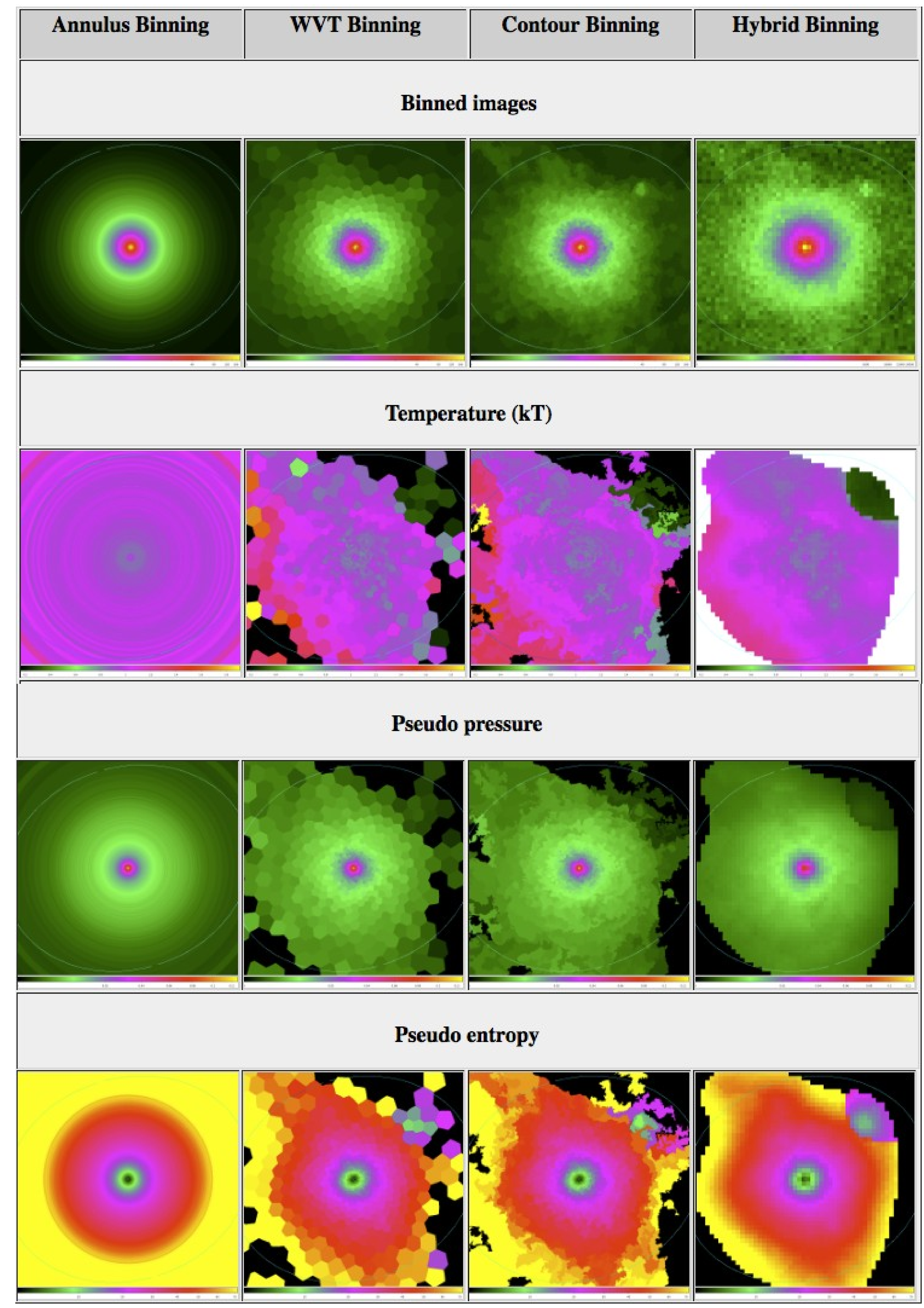
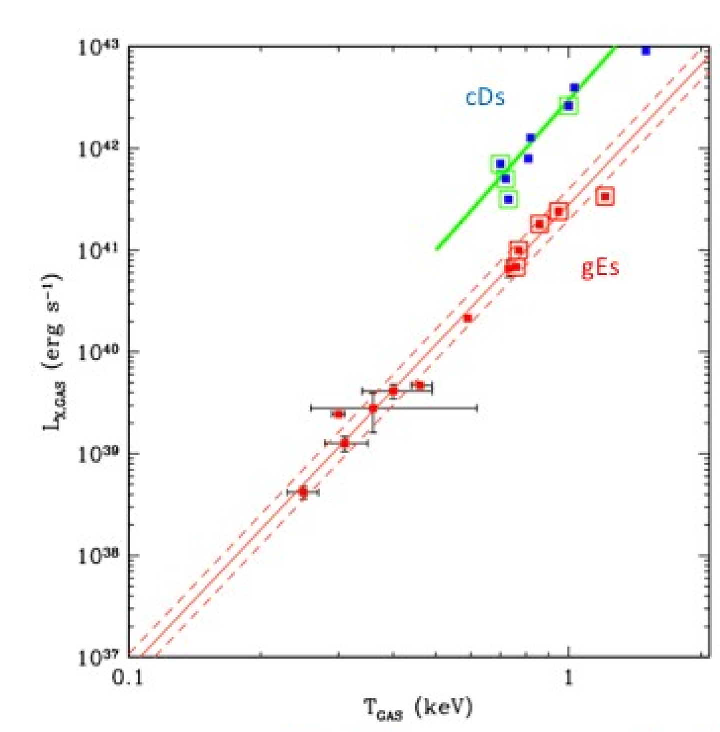


Figure 2. Spectral maps of the hot ISM in NGC 4649 made by four adaptive binning methods. The 2nd row shows the asymmetric hot gas distribution with the extended tail toward the north-east and the south-west (see also Woods et al. 2017). The first T map shows a rather complex profile. T decreases with increasing radius in the inner region, and then increases in the outer region (see also Humphrey et al. 2013 and Paggi et al. 2014). The negative gradient in the central region is likely related to the AGN while the positive gradient in the outskirts is likely related to the hotter gas associated with the galaxy cluster in which NGC 4649 resides. The next three 2D T-maps further show more complex temperature structure; the cooler region is more extended toward the north-east and the south-west, indicating the asymmetrical features are extended from the center to the outskirts. In spite of this galaxy being extensively investigated, this 2D temperature structure was discovered for the first time in our program.

Example of Global Properties

cDs vs. gEs
in the $L_{X,GAS} - T_{GAS}$ relation



gEs – giant, old, σ-supported Es with a core
(e.g., N1407, N4552, N4649, N4472)

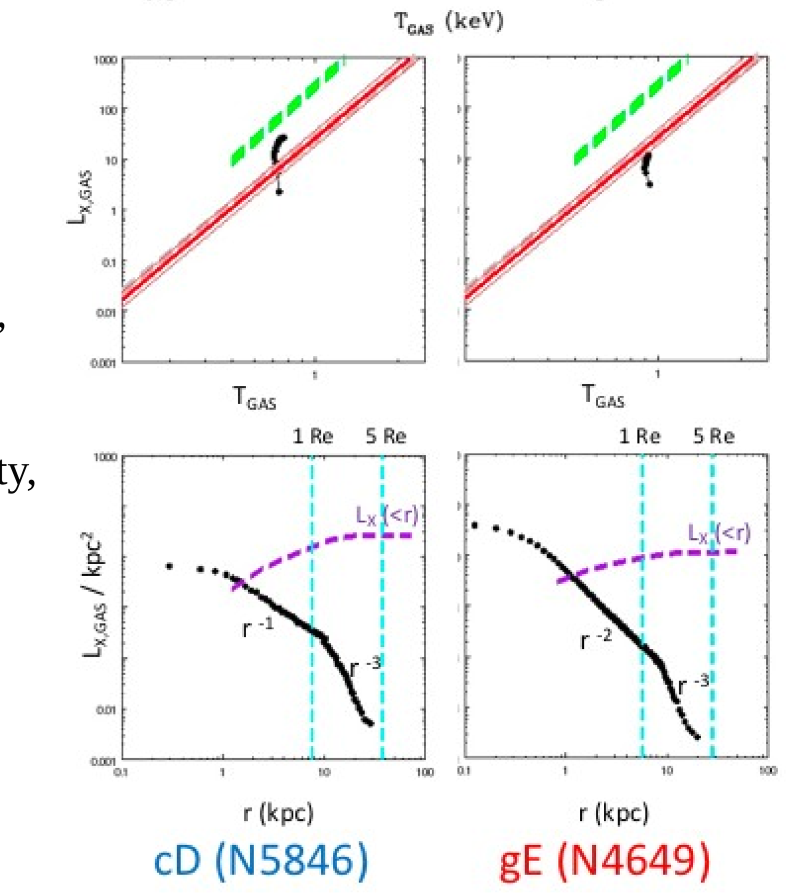
cDs – dominant E at the center of a group
(e.g., N507, N5044, N4636, N5846, N7619)

What makes cDs more luminous with similar T?
(from Kim & Fabbiano 2015)

Inner region r = 1-10 kpc (< 1.5-2 Re)
radial profiles flatter in cDs

	cDs	gEs
$L_{X,GAS}$ / area	r^{-1}	r^{-2}
n_e	r^{-1}	$r^{-1.5}$
emissivity	r^{-2}	r^{-3}
entropy ($T/n_e^{2/3}$)	$r^{2/3}$	r^{1}
Pressure (n_eT)	r^{-1}	$r^{-1.5}$

Outer region r >10 kpc (> 1.5-2 Re)
radial profiles – similar
$L_{X,GAS}$ / area ~ r^{-3} ; n_e ~ r^{-2}



$L_{X,GAS}$(total) and $<T_{GAS}>$
almost determined in the inner region

total mass in the gas extent: similar
cannot make L_X different

disturbed gas morphology in cDs
(e.g., sloshing, AGN feedback)
redistribute the gas in the inner region
clumpiness – also increases L_X (~ n_e^2)

consistent with more cold gas/cooling in cDs
(lower, flatter entropy at r < 10 kpc)
by Werner et al. (2014)

X-ray based mass profiles in the inner region
could be misleading !
(see Paggi et al. 2017, ApJ, 844, 5